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Fiber Lasers

At DARPA's Tactical Technology Office, we are engaged in the development of a new and innovative concept for high power fiber lasers. These are the fiber lasers.

High-powered fiber lasers provide a quantum leap in defense capabilities for the warfighter and would contribute to transformation of the military to better respond to both force-on-force and asymmetric threats. But first, let me explain the capabilities and limitations of the various types of lasers.

Chemical lasers, which derive their output power from chemical reactions in a supersonic gas mixture, are capable of delivering lethal amounts of energy against in-flight missile targets. These lasers include hydrogen and deuterium fluoride (HF and DF) and chemical oxygen/iodine lasers (COIL). Chemical lasers, however, have limitations, such as the limited magazine size and the corrosive effects of toxic waste.

In contrast, solid state lasers derive their energy from optically pumping or exciting rare earth elements embedded in a crystalline or glass medium to an excited state at a higher energy level and then decay to ground state. They have shorter wavelengths, are environmentally benign, and have less demanding logistics requirements. High-power solid-state lasers are in the early stages of development. To achieve high average powers, large sizes of solid-state laser materials are required.

The efficiency of flash lamp or laser diode pumped solid state lasers is limited by thermal management requirements.

Fiber lasers are a new generation of laser diode pumped solid state lasers. They have a high wall-plug efficiency (~20 percent or greater) and unique advantages compared to other lasers. The very large surface-to-volume ratio simplifies thermal management or heat removal, and this enables robust packaging for maintenance-free operation.

Single-mode fiber lasers have the smallest beam divergence and high power density and brightness or signal intensity. The radial intensity profile is uniform in a plane perpendicular to the direction of propagation and constant phase—the position of wavefront at a time  $t$ .

If multiple single-mode fiber lasers have the same phase for the wavefronts and polarization—that is, the direction of the electric field perpendicular to the direction of propagation—the intensity adds coherently in the farfield through constructive interference. This opens up the possibility of coherently combining many single-mode fiber lasers to provide high output powers.

The existence of an advanced and well-developed telecommunications industry base allows a more rapid development of innovative fiber laser designs and will advance the state of the art of high power fiber laser technology. These advantages must be further explored and utilized in order to realize the potential of high-power fiber lasers.

Single-mode fiber lasers would have a rare-earth doped core, or the central gain region of the fiber on the order of few micrometers ( $\sim 5$  to  $7\ \mu\text{m}$ ), and a cladding surrounding the core configured to guide the laser diode pump power. The index of refraction  $n$ —ratio of velocity of light in vacuum to material, of the cladding is less than that of the core. This property confines the laser diode pump power around the core. The small cross-sectional area of the core region severely limits the achievable output power operation of the fiber lasers due to optical damage and nonlinear effects that compromise the spectral quality.

Single-mode fiber lasers with output powers of 100 watts and diffraction limited beam quality with most of the energy in the central lobe are available commercially today. However, the polarization is not in a single direction due to the circular core region.

To increase the output power beyond 100 watts, new techniques for large mode are fibers with a core diameter on the order of tens of micrometers must be developed.

In addition, we should develop techniques for polarization preservation and maintain single transverse mode with excellent beam quality. Such lasers would mitigate the onset of nonlinear effects. Additionally, concepts for launching high brightness laser diode pump power in the cladding region are needed. Conventional fibers have a higher index of refraction for the core region and a lower index of refraction cladding region.

As I mentioned, light propagates in the core, experiencing shallow reflections at the interface core and cladding due to the differences in index of refraction.

Recently, a new kind of fiber structure was demonstrated—the so called photonic crystal fiber or "holey" fiber. The holey fiber is so named because of arrays of microscopic air gaps or capillaries arranged in a periodic pattern like a crystal lattice along the length of the fiber. Light is scattered and confined or trapped in a region depending on the size and spacing of the capillaries. If the capillaries are replaced by a solid region in the center or made entirely hollow, one can form a solid or hollow core that is embedded within the photonic crystal or holey fiber. Complex patterns can be designed to provide an effective index of refraction that is lower than the solid core.

Regularly patterned two-dimensional micrometer scale air gaps or periodic structures similar to crystal lattices can be created that run throughout the length of the fiber and scatter light selectively into the hollow core. This is a remarkable property in that there are no materials with index of refraction less than air, and yet light is confined to the hollow core. For particular wavelengths and angles of incidence, light is back-scattered into the hollow core by air holes in the cladding. This results in constructive interference of all rays back into the core. This makes it practical to have larger core regions, which can carry more optical power compared to conventional fibers minimizing the nonlinear effects.

Preforms from which this photonic crystal fiber are drawn are prepared by closely stacking silica capillaries and rods. This approach provides flexibility in incorporating doped cores or rings, hollow cores, and birefringent cores for polarization preservation. This remarkable capability can be exploited to obtain polarized single-mode high output power from a single fiber laser.

The output power of a single fiber laser cannot be extended beyond a certain power level without compromising the advantages and flexibility of fiber lasers. To do so would result in the fiber laser becoming the equivalent of diode pumped solid-state rod laser. However, if the output wave fronts of multiple fiber lasers are in phase and same polarization, the output powers may add up coherently to provide high power output. This requires precise control of the polarized phase of the output wave front, using linear or nonlinear phase combining approaches.

Fiber lasers are long (typically, several meters) and small thermal drifts lead to large variations in output phase. Phase control, or locking the phases of many fiber lasers, may require sensing and active control of individual fiber laser output phases through phase modulators. This can be accomplished, for example, through the spatial light modulators (SLMs) based on micro-electro-mechanical systems (MEMS) that are being developed in the Coherent Communications, Imaging, and Targeting (CCIT) Program.

Phase control may also be accomplished by nonlinear approaches such as using phase conjugate mirrors. A diverging beam continues to diverge upon reflection from a conventional mirror.

Phase conjugate mirrors, on the other hand, reverse the direction of the wavefront to the original starting point through reflection from a phase grating formed from nonlinear processes in a media.

To realize the full potential of high-power fiber lasers, DARPA has formulated a high-risk/high-payoff research and development program to develop high-power fiber lasers. The technical challenges are to develop single-mode high-power fiber lasers with polarization preservation, launch laser diode power into

the fiber cladding, and control the phases of many fiber lasers to coherently combine the output to provide high average power in the far field.

This program has two separate tasks. In the first task, single-mode fiber lasers with output powers of 1 kilowatt or greater from a single aperture will be developed and demonstrated. In the second task, tens of kilowatts output power and capability to scale to greater than hundreds of kilowatts output power and beyond will be demonstrated through coherent combining of the output power from multiple single-mode fiber lasers.

These two tasks will be executed in two 18-month phased efforts. The phased approach provides a go/no-go decision point to determine if the effort is progressing toward achieving or exceeding the objectives of the program or to determine if the technical risks are insurmountable.

The two tasks of this program require distinct core competencies or expertise and a knowledge base. The first task requires an understanding and expertise in the design and fabrication of fiber preforms with a tailored index of refraction profile of the core and cladding region in order to control of the effects of nonlinearities and multimode output from LMA fibers, polarization preservation, and launching of high-power diode arrays. The second task requires an understanding of and expertise in fiber laser systems, phase control for coherent combining of multiple single-mode fiber lasers, and system integration issues.

Early evaluation of design concepts, feedback, and enhancements toward reliable and affordable systems are critical to the success of achieving or exceeding the objectives of this program. This approach enables an implementation-ready technology development and significantly reduces the acquisition life cycle of the four Military Services' acquisition plans.

In summary, coherently combined high-power fiber lasers with output powers beyond 100 kilowatts will provide a quantum leap in Defense capabilities. The unique advantages of fiber lasers enables scalable and robust packaging architectures for operation in harsh environments by simplifying the logistic tail and providing a deep magazine, limited only by electric power, in a compact footprint. Besides electric power, these lasers do not require consumable supplies, create no environmental waste or toxic pollutants, and can be deployed on land, airborne platforms, and ships for platform self defense.

Thank you.